Management of buffer systems in automotive stabilized production networks - a qualitative analysis

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Abstract

Automotive manufacturers are operating in global and cross-linked production networks. From a productions and logistics point of view they act as consignors and consignees of material, components and car bodies within these networks. The demand for customized cars, rapidly changing market environments, local market regulations and technology leaps force companies to orient their operational activities towards more flexible and resilient production strategies. One promising method to deal with the evolving complexity, uncertainty and volatility is to establish a stabilized production system. This concept requires several prerequisites, above all a high degree of stability in the production process. Buffers are allocated to perform multiple functions in order to provide stability. Opposing objectives of stakeholders, unfavorable infrastructural settings and the lack of an integral planning process can be an obstruction towards effective buffer allocation in production networks. If not applied in an integrated approach considering all functions buffer capacity can lead to an adverse effect on the overall performance. Misaligned buffers lower the efficiency, reduce the flexibility and increase the complexity of production systems. This article presents trade-off observations and challenges system designers are confronted with during the allocation of buffers in stabilized production networks. The most significant trade-off is between the two competing objectives of stability and throughput. Best practice on how to implement buffers and manage the arising trade-off are presented.

Keywords: automotive production network, management and organisational control, stabilized production, buffer allocation, design of effective production

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1. Introduction

Customization allows consumers to specify the products to their desires and is a current differentiating strategy chosen by many car manufacturers to compete in the highly competitive market (Brabazon et al., 2010; Kasiri et al., 2017). Manufacturing customized products with personalized features is facilitated by new technologies and concepts of Industry 4.0 (Wang et al., 2017). Market regulations increase production variety offered by original equipment manufactures (OEMs) even more (Ito and Sallee, 2018). To cope with the expanded model mix as well as variants in equipment options OEMs outsource sub-assemblies to shift product variety to upstream suppliers. Thereby, they diminish vertical integration at the production site and benefit from lower production and handling costs (Swaminathan and Nitsch, 2007). Saving costs by sourcing components to low wage countries is a long-standing trend and increases the quantity and geographical dispersion of suppliers. As a result of these developments, cars already comprise between 4,000 and 9,000 different components and the count of suppliers exceeds 1,000 (Unger, 2018). As a consequence of these trends OEMs are operating in highly global and cross-linked production networks (Bozarth et al., 2009; Boysen et al., 2011; Ruppel, 2015; Modrak et al., 2018).

From the perspective of an OEM complex production networks are difficult to design and manage (Wagner and Silveira-Camargos, 2012; Ivanov and Dolgui, 2020). One common approach to deal with the complexity of supply chains is to establish lean production concepts such as a stabilized production system (SPS). Leanly operated production sites are more capable of simultaneously achieving high levels of productivity and quality (Krafcik, 1988; Shah and Ward, 2003). To fully exploit these advantages a constant and high stability level within the network is necessary. In this context stability means that the production requirement forecast equals the actual production requirement (Inman and Gonsalvez, 1997). Many OEMs are stuck in a transformation process or struggle to maintain a constant and high stability level (Womack et al., 2007; Meissner, 2010; Lehmann and Kuhn, 2019). Blocking and starving as well as stochastic processing times are drivers for instability (Battini et al., 2009). Intermediate buffers for car bodies and components are allocated to compensate these effects. Buffers fulfill several functions, such as decoupling flow lines or re-sequencing the order (Müller and Kuhn, 2020). Production steps require different sets of buffer functions. However, the range of functions applied determines the type of retrieval strategy required, e.g., random access or first in first out, and therefore they define the type of buffer needed, e.g., automated storage and retrieval system (AS/RS) or mix bank. As these types require different investment and restrict the limited floorspace to different degrees the assignment of buffer functions is an essential task for the long- and mid-term planning process of production networks.

In this article the operative processes that are carried out in case of sequence instability are linked to the required buffer functions. Furthermore, planning steps to successfully implement and manage buffer systems in real-world manufacturing systems are put into a framework and described in detail. To provide potential for further research arising trade-offs are revealed. A supportive organisational environment and favorable production setting facilitate the allocation and management of buffers in stabilized production networks.

The paper is structured as follows. Section 2 gives an overview of stabilized automotive production networks and envisions concepts to allocate buffers within this setting. The planning steps to allocate and implement buffer systems are given in section 3. Trade-offs system designers are confronted with and a buffer setting favorable to SPSs are discussed in Section 4. A summary and prospects for future research in Section 5 conclude this paper.

2. Buffer allocation in stabilized production networks

In order to provide customized cars OEM's establish built-to-order strategies on highly flexible mixed model assembly lines (MMAL) (Boysen et al., 2008; Volling et al., 2013). Production starts when the customer order is received and at the beginning of the production the costumer order is assigned to a car body (Meyr, 2004). These concepts are integrated into complex production networks.

2.1. Automotive production networks

Automotive production consists of the physically connected body shop, paint shop and final assembly line as well as buffer systems. Common descriptions of the production process conclude a simple one line production flow (Choi and Lee, 2002; Pierreval et al., 2007; Fournier and Agard, 2007; Boysen et al., 2015). Compared to real-world production systems, this single-line car body flow is an oversimplified assumption. The schematic overview in Figure 1 illustrates a fully assigned production plant embedded into a network. It contains the car body flow (CBF) along with the component flow (CF). The CBF is sequentially organized, but production segments comprise several assembly lines. The resulting number of possible connections correspond to the number of potential CBF routings. There are two main buffers located in the CBF; one between the body/ paint shop and the second one between the paint shop/ final assembly. CFs are bidirectional as plants are a producer of components for other plants (source) or consignees (sink). Suppliers of components are either incorporated sub-assembly lines, other production sites or subcontractors. The CF includes buffer systems which are located at sources and sinks of connecting lines. In some networks an additional buffer, e.g., a distribution center to prepare JIS material, is located in between sources and sinks.

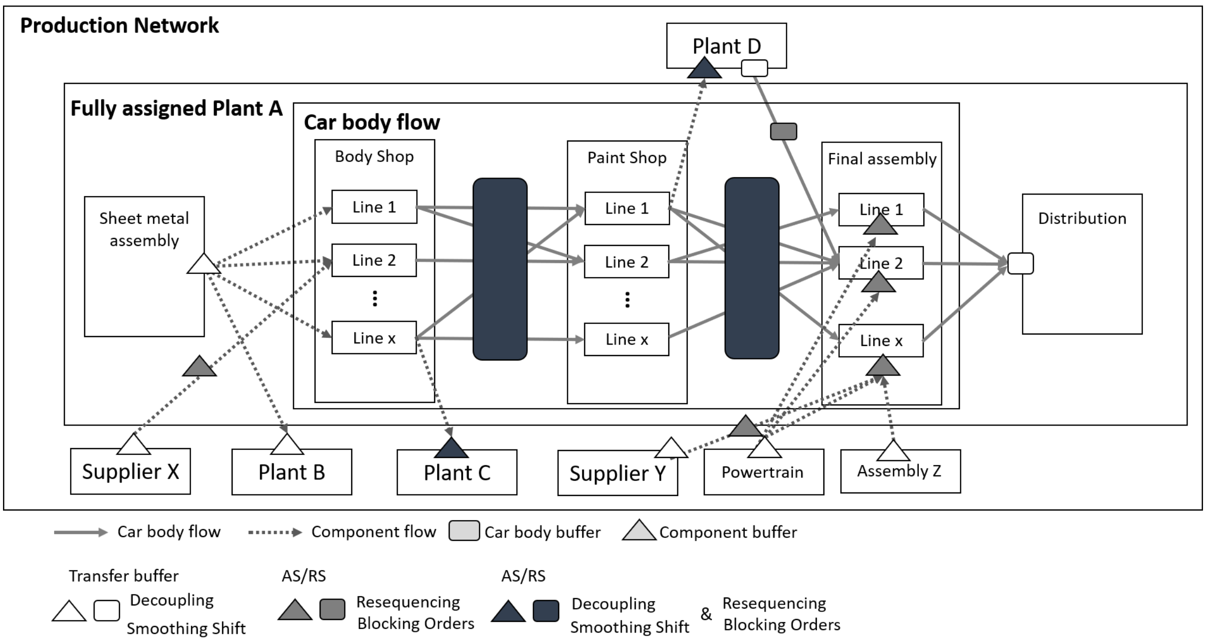

Figure 1: Schematic overview of buffer functions and locations in automotive production networks

Current developments in the automotive sector reinforce the expansion of the described networks. OEMs establish new cooperative ventures, e.g., with computer or telecommunications companies, to adapt non-automotive technologies (Attias, 2017). Manufacturers in the premium segment use purchasing cooperations, distribution networks and production platforms as an entry into less expensive segments (Göpfert et al., 2017). This step is necessary to meet the cost pressure as well as to manage the enormous variety of parts and components. Thus, operating production networks efficiently and ensuring a stable CBF as well as CF is the key success factor of OEMs nowadays (Gehr and Hellingrath, 2007).

2.2. Buffer functions in stabilized production systems

Key aspect of the SPS is planning and scheduling the sequence for the final assembly line several days before the start of the assembly process (Meissner, 2010). Figure 2 displays an SPS with JIS delivery patterns (Müller and Kuhn, 2020). A scheduled production and delivery date which serves as a requirement forecast is provided to costumers and suppliers. The fixed schedule and corresponding requirement forecast is the baseline for optimized material supplying approaches and reduces logistics handling expenses (Inman and Gonsalvez, 1997; Lehmann and Kuhn, 2019). A constant high stability level is the prerequisite for the applicability of the SPS concept. Stability means that a vehicle is manufactured exactly at its planned position in the sequence and at the fixed production time. Different key performance measures (KPIs) are applied to evaluate sequence stability (Müller et al., 2020). Sequence deviation, e.g., delayed or advanced orders, is penalized based on different calculation approaches.

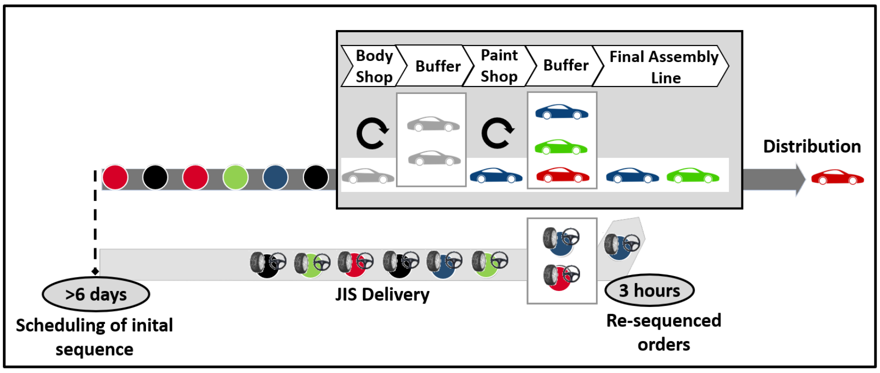

Figure 2: Automotive manufacturing in a stabilized production setting

The source for the requirement of buffers in production systems is variability, e.g., variability in process times, delivery times or demand rates (Hopp and Spearman, 2004). Buffers in SPS are required to maintain a constant high stability level and fulfill four functions. Foremost they serve as a decoupling module and avoid blocking and starving as it limits the throughput of the production (Shi and Men, 2003). Process blocking occurs when there is no more space to store work in process (WIP). When a production unit is idle and is forced to stop it is called starvation. Furthermore, buffers enable different takt times and shift models between production steps. The takt time of a production unit is the average time between the start of production of an order and the start of its successor. In production networks takt times vary, resulting in varying throughput per hour. To balance overall output different shift models are applied (Wang et al., 2010). The stock in the buffer increases and decreases in regular cycles depending on the type of shift model. A number of car bodies is required to mitigate scrambling effects and re-sequence the sequence initially planned (Inman, 2010). Another function of buffers is to store blocked orders (Müller and Burges, 2020). If an order cannot be assembled at its original position it is blocked and the car body is stored in the buffer.

Buffer types engaged define possible arrival and retrieval strategies (Müller and Kuhn, 2020). Figure 1 gives an overview where buffer functions and types are commonly positioned in supply networks. To decouple production steps and to smooth differing production rates or varying shift models there is no special request towards the succession when retrieving orders. To carry out the re-sequencing and blocking function an AS/RS for the CBF and CF is mandatory. The linkage between the scrambling of an order and the requirement on car and component handling is exposed in Figure 3. It displays typical JIS supply patterns in SPS. The sequence of the CBF determines the order of material supply (Choi and Lee, 2002). If an order is blocked several operational tasks are executed (Boysen et al., 2015). From a logistical point of view material has to be re-sequenced; all components for blocked orders (number 6) are buffered and material for pulled ahead orders (number 7 and 8) are moved forward. The impact on the CBF is similar; blocked car bodies are stored in a buffer and succeeding orders are pulled ahead by one position.

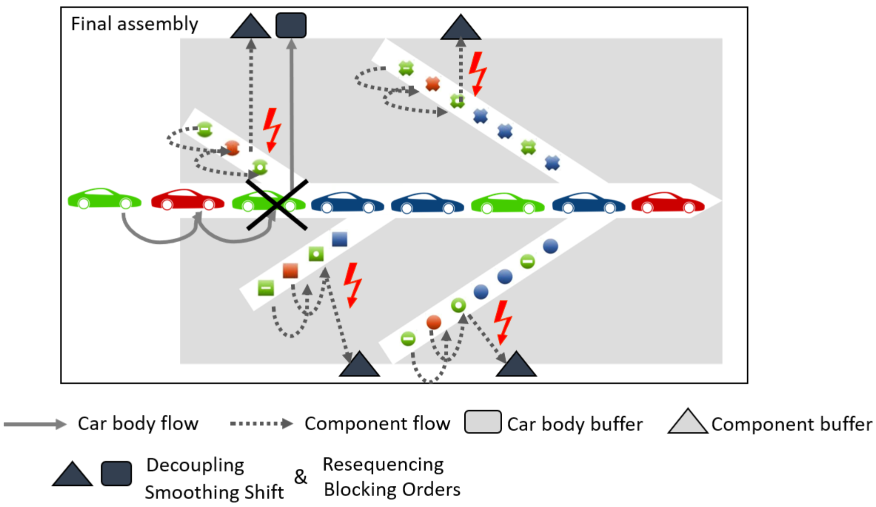

Figure 3: Impact of sequence scrambling on buffer requirements

2.3. Critical review on buffer systems in stabilized production networks

Buffers do not only give rise to advantages but imply some negative effects. They increase the WIP, raise the lead time, enhance investment and decelerate customer response (Glasserman and Yao, 1996; Kim and Lee, 2010). Additionally, they cover the limited floor space close to the assembly line (Lehmann and Kuhn, 2019). Buffers with random access require even more floorspace, a higher investment as well as operational expenses compared to mixed banks with parallel or loop lines (Inman, 2010). A steering logic is required to integrate them into the CBF as well as CF and to maintain a balanced stock (Van der Duyn Schouten and Vanneste, 1995). Too large or too small buffer capacity in stabilized production networks will lead to a number of disadvantages as displayed in Table 1. In the medium run both conditions lead to a decline of production efficiency.

Buffer capacity too high	**Buffer capacity too low**
Redundant functions and waste streams	Limited functions and restricted usability
Inefficacy of additional buffer capacity on the degree of stability	Instability and increased presence of scrambling
High amount of WIP, fluctuation of throughput and increased lead time, delays in delivery schedule	Loss of throughput because of blocking and starving, limited capability of smoothing shift models, limitation of operational intervention options
Additional costs on provision of resources, WIP, accumulation of operational processes, augmented complexity and opacity	Lost profit margin, additional costs on increased material handling effort and additional working shift

Table 1: Impact of misaligned buffer capacity

3. Planning and management of buffer systems in stabilized networks

A variety of planning problems arise when stabilized production networks are installed. An important long- and mid-term planning problem is the allocation of buffer systems and appendant functions. It comprises the stages of prearrangement, implementation and planning operational control processes. Figure 4 shows planning problems system designers are confronted with during the implementation. These are dealt with in the following.

Business Case. Stabilized systems require buffer types with random-access such as AS/RSs. A study on the impact of buffers helps to underline their potential benefits and recoverable amortization rate. In real-world manufacturing networks the impact on throughput is clearly measurable while sequence stability and its effects are difficult to quantify (Alden et al., 2006). The business case is based on considerations of production networks with no or little buffer capacity. Therefore, the production volume of the production steps are examined retroactively

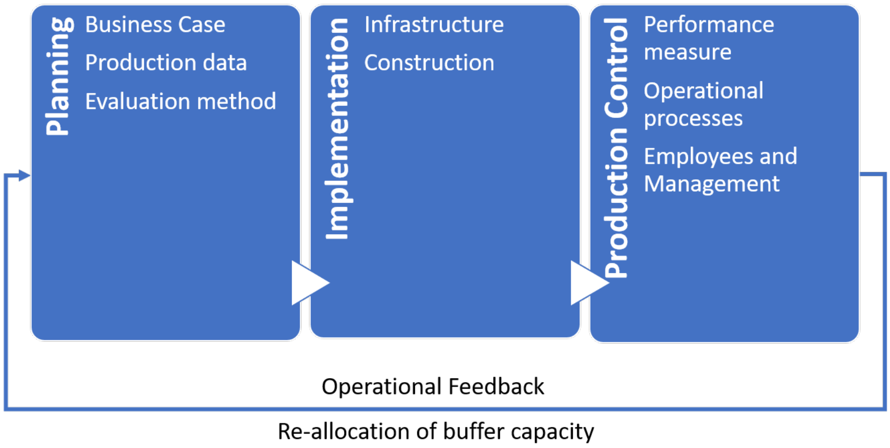

Figure 4: Planning and management of buffer systems in stabilized production networks

for a longer period of time, e.g., one year. Units that cause bottlenecks and reduce the planned throughput of production networks are of special interest. Loss in throughput is caused by unexpected downtime. In some cases additional working shifts are applied to compensate the minus. Loss in sales and resultant lack of profit margins as well as costs of additional shifts are priced by the controlling department. To calculate the amortization rate of an AS/RS the initial investment to install it is set into ratio with total costs of deficiency.

Production Data. The fundamental requirement to create a business case or to conduct studies is the availability of high quality data from the manufacturing system (Alden et al., 2006). The huge amount of data necessary to describe operational processes can be difficult to collect (Pierreval et al., 2007). All stakeholders of the process need to store relevant data consistently and with a sufficient level of quality. Another important issue is to harmonize production data collection by determining the frequency as well as the storage time (Kusiak, 2017). Especially in large production networks it is useful to establish a centralized database management to coordinate the manufacturing data throughout networks and ensure their integrity. The application of a data retrieval tool and a web-based management execution system (MES) to systematically track and document the transformation of the car body to a finished car is essential (Bourne et al., 2018). Responsibility of data management and data ownership has to be clearly defined. Data sovereignty should be assigned to operative production control centers in order to guarantee quality, completeness and accuracy. Furthermore, the operative production control centers should engage data analysts. They interpret, visualize and prepare production data as basis for decision-making.

Evaluation Method. The buffer allocation problem translates into an optimization problem opening a wide field of research. For a classification scheme and literature review see Demir et al. (2014) and Weiss et al. (2018). Analytic approaches on allocation of buffer space in flow lines take stochastic behaviour into account. However, these models are subject to limitations and assumptions because otherwise they would become too complex to calculate. Discrete event based simulation (DES) is commonly used to analyse real-world manufacturing systems and to address the buffer allocation problem without making limiting assumptions (Mahadevan and Narendran, 1993). DES is particularly suitable for the evaluation of complex queuing networks with limited buffer capacities and stochastic production times as well as the analysis of effects of the variables and their interactions (Montevechi et al., 2007; Alfieri and Matta, 2012; Siebers et al., 2017). It only takes into consideration events that are of importance to the further course of the simulation, e.g., a car body entering a production step or leaving it. This method is efficient in terms of performance and allows system engineers to simulate production processes over a large period of time within minutes. In addition to the expertise of a simulation specialist DES requires production process know-how and extensive data sets. Information on production layouts, operating procedures, model parameters and product details need to be recorded and prepared. This induces further challenges, e.g., finding a suitable level of detail which suits the data availability and scope of the project. Modeling the functionality of certain instances as black boxes and embodying their effects in the applied data is one solution to avoid an unnecessarily high level of detail. The effort spent on deliberately choosing and developing a simulation model pays off in the long run. It avoids trial and error solution-seeking and helps system designers to prepare business cases and to forecast the performance of production networks.

Infrastructure. Once buffer functions are determined and capacity computed, performance demands are calculated and the most suitable location is selected. The criteria for determining the construction site include available clear height, size, quality and weight of car bodies as well as type of storage and retrieval systems. AS/RSs consist of storage racks, inbound/outbound stations and the most expensive part: cranes (Roodbergen and Vis, 2009). When an AS/RS is physically implemented the limits of its operating capabilities are fixed. Thus, the required throughput must be defined in advance. The performance of a system is defined as the number of storage and retrieval requests performed per time period (Bozer and White, 1982). The physical design determines performance and investment. Choosing more aisles reduces rack length or height if the capacity is maintained, but this design requires additional cranes. Shortening or lowering aisles reduces traveling distances and retrieval times, i.e., increases throughput.

Construction. The construction of buffer systems is seldom a greenfield project, i.e., they are integrated into existing networks. Transforming established production networks which are currently operating under different premises into an SPS is challenging (Lehmann and Kuhn, 2019). The expansion of infrastructure in brownfield projects is often not possible during operating time, which means it is bound to vacation closedown or will cause additional downtime. The second option leads to high opportunity costs. The planning of the implementation of a construction project has to start well in advance in order to adjust construction requirements to the ongoing production.

Performance Measurement. In SPS KPIs evaluate various parameters such as throughput, buffer filling level and stability level (Buchkin, 1998). It is important that the applied KPIs are discussed and agreed on with all stakeholders of the production network as well as reported on a regular basis. Suitable KPIs which reflect the status of the stabilized production network must be developed and implemented. E.g., the KPI stability level displays the effort of operational processes when changing the sequence initially planned by quantifying the amount of materials handling and the required buffer capacity (Müller et al., 2020). The target value of the stability level depends on the infrastructure and buffer capacity of the production network. By conducting simulation experiments, calibrating parameters and analyzing results an appropriate stability level can be estimated.

Operational processes. Optimal buffer filling levels identified by means of simulation experiments need to be maintained throughout production networks. Exceeding or falling below the planned buffer filling level has far-reaching consequences as describes in Table 1. Since buffer functions mentioned are only feasible if the filling level is steady, sensible operational control procedures need to be applied. An important prerequisite is to identify and compensate throughput losses immediately. Production units execute counter-measures such as additional working shifts on short-term. Another essential task in highly cross-linked, international production networks with JIS delivery approaches is decoupling differing shift models.

At best, working hours of production units joint by source / sink connections coincide. Differing working hours and varying public holidays enlarge buffer capacities required and limit the applicability of JIS strategies.

Employees and Organisation. The buffer allocation and operational processes are adapted towards requirements of SPS which restricts manufacturing managers and stakeholders in their decision-making. Limitations might reduce the efficiency of individual production units. Often, management incentives have not been restated or are aligned to short-term goals, e.g., throughput, and do not reflect effects on the stability level. The refusal of management and employees impede to fully leverage potentials of SPS. Lack of cooperation and in the worst case, rejection on an operational level is often caused by a gap of knowledge and information. Improving the understanding of SPS and buffer functions is one factor of success. Coordinating and conducting training sessions as well as the application of multipliers to pass on knowledge and experience is important. In this context it is necessary to adapt the cooperate culture towards lean, transparent and holistic viewpoints. Promoting a zero-defect culture and dealing with errors openly is a crucial success factor.

Monitoring and evaluation of buffer systems. Stabilized networks are sensitive constructions which need continuous adaption to new production settings. Re-allocating buffer capacity is required whenever there are substantial changes in product specifications or production settings (Xu et al., 2011). E.g., a major change of product assets when introducing a battery electric vehicle (BEV).

4. Strategic decisions in stabilized networks

A multiplicity of trade-offs arise when analyzing production networks. The concept of a trade-off suggests a scope for decision-making with full comprehension of advantages and disadvantages of each setup. The trade-offs occurring in SPSs mainly result from the requirements of the system along with the physical limits of buffer capacity. Both restrict production units in their decision-making.

Trade-offs. In SPS the production sequence of CBFs and CFs are aligned with the sequence of the final assembly line. Consequently, all upstream production segments are limited in modifying the sequence according to their needs. E.g., body and paint shop are restricted in building body shell batches or paint batches. The limitation reduces the productivity of production facilities and leads to decreased local efficiency. Furthermore operating flexibility by compensating local throughput losses via counter-measure on short notice is a prerequisite to maintain stability. The resulting trade-off between benefits of individual production sections and comprehensive interests of the network need to be managed. Another question emerges considering measures to compensate negative effects of downtime over an extended period of time. Production losses can be offset by the balancing effects of buffers or through flexible production operations, such as running an extra shift. Whereas the first solution requires a high investment to provide the infrastructure, the latter has an impact on the contract of employment and implies high short-term variable costs caused by higher salaries.

The goals of sequence stability and throughput can not be attained simultaneously in SPS with limited buffer capacity, hence several trade-offs arise. In the CBF there is a conflict of target-setting when it comes to the management of the buffer functions. It is reflected in the utilization of buffer capacity. Re-sequencing maintains the stability level and decoupling production steps as well as smoothing shift models ensures a constant throughput. A certain amount of buffer capacity is required for re-sequencing, if the number decreases the stability level is reduced. If the capacity for decoupling is reduced blocking and starving occurs which lowers the throughput of production networks. Consequently, if the buffer filling level falls below the planned level a trade-off between throughput and stability level arises. A similar trade-off occurs in the course of the production process when orders overtake defected orders which are redirected to repair loops or off-line repair stations. This causes scrambling and lowers sequence stability. There are steering approaches such as line stop strategies to avoid scrambling (Robinson et al., 1990). The assembly line stops until defected orders are repaired, provoking a decline in the throughput (Han and Park, 2002).

At the final assembly there are several trade-offs concerning re-sequencing strategies (Lahmar and Benjaafar, 2007; Lim and Xu, 2017). It might be beneficial to ignore certain sequencing rules in order to maintain the stability (Boysen et al., 2010). This causes an unbalanced workload at the assembly line and induces costs, e.g., for additional workers. In case of defect or missing material orders are blocked or dispatched into the final assembly. The first causes scrambling and the second causes rework after the assembly line generating additional costs.

Organisational environment. The implementation of stabilized networks discloses an organizational problem which is beyond the tools and methodology of buffer allocation. A superior body independent of local concerns of the production segments has to balance the arising trade-offs. The management needs to place the decision-making authority and competence into the hands of a superordinated control, e.g., the operative production control center (Daniels and Burns, 1997). It decides which KPIs are taken into account and whether stability or throughput should prevail in the current status of production. Furthermore, clear responsibilities in inventory management ensure efficient as well as sustainable management. The optimum buffer filling levels are determined centrally and the responsibility for maintaining them is decentralised.

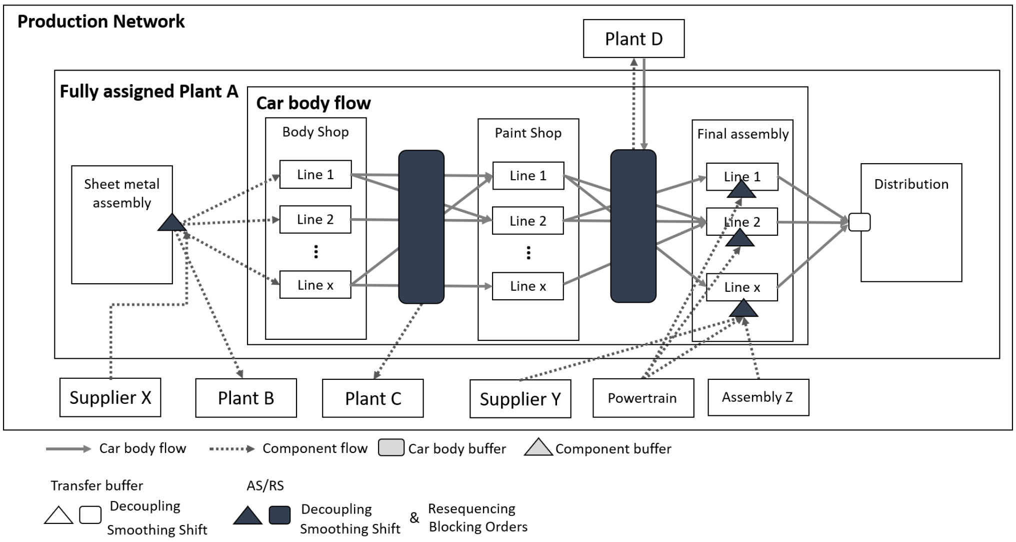

Figure 5: Favorable production setting in stabilized automotive production networks

Production setting. Most of the observed trade-offs in stabilized production networks are related to the allocation of the limited buffer capacity. To avoid excessive capacities and increase the flexibility of stabilized systems one shared buffer should be allocated at each connecting source-to-sink line. The functions of the buffers are transparently assigned and there is a clear structure. Figure 5 displays a favorable production setting. Compared to Figure 1 the number of buffer facilities in the network is significantly reduced. The required buffer capacity of connecting and intersecting lines are merged in one shared buffer. A shared buffer has a balancing effect on stock levels and flexibly exploits the available buffer capacity (Matta et al., 2006). It can significantly reduce the required buffer capacity in unreliable flow lines (Müller and Kuhn, 2020). Furthermore, shared buffers facilitate a clear responsibility for the control of inventory and replenishment, which is an important factor to avoid the bullwhip effect (Lee et al., 1997).

5. Summary and further research

This paper tackles the question of how to allocate buffers in stabilized automotive production networks effectively and efficiently. JIS supply chain patterns are prevalent in these networks and induce the necessity of stabilized production environments. Buffers are required to ensure the stability as well as throughput and fulfill several functions. Therefore, an optimal buffer filling level determined by means of a simulation study must always be maintained. Both too high as well as too low capacity lead to disadvantages and decrease productivity. An optimal set up of buffers consists of shared buffers that cover all required functions and reduce the total amount of required buffer facilities. Allocating buffers in real-world manufacturing networks confront system designers with a broad spectrum of obstacles and trade-offs. Most of them are connected to the requirements of stabilized systems and the physical limits of buffer capacity. Production units are limited in their decision making to maintain the stability level of the network. There is a trade-off between keeping a high level of stability and maintaining the throughput. A centralised decision-making authority should balance the level of stability and throughput.

While this paper is intended to stimulate discussion and enlarge the research agenda of stabilized production networks, it offers several opportunities for future research. To quantify effects of sequence scrambling or instability is a research question of practical relevance. The planning problems and obstacles system designers are confronted with could be further investigated. Future studies should take the trade-off between sequence stability and throughput into consideration. Therefore the costs generated by additional material handling and throughput losses should be identified and optimized. A next step could be to conduct a large-scale empirical survey in order to expose efficient stability levels for different production settings.

Research on stabilized production systems certainly is important for the advancement of efficient manufacturing in the automotive industry. Extending this concept to more sustainable production would be a highly up-to-date topic. Additional research is needed to adapt the concept to other industries, e.g., the health care or retail food sector.

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